

Interstellar Magnetic Field Studies and Requisite Detector Properties

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Abstract

Magnetic fields play important roles in cloud, cluster, and star formation. Yet magnetic fields are exceedingly difficult to detect and trace. The current best method involves measuring far-infrared linear polarization of aligned, spinning, thermal dust grains. SOFIA instruments and Small Explorer (SMEX) missions have been proposed that would routinely measure interstellar magnetic fields. But, these instruments and missions require far-infrared array detectors with superb sensitivity, noise immunity, photometric accuracy, and electron well-depths. Current unstressed Ge:Ga photoconductor arrays meet some of these requirements, but not all. Bolometer arrays require cooling and operating accommodations incompatible with SMEX mass, volume, and cost constraints. Based on models of SMEX and SOFIA instruments designed to efficiently map interstellar magnetic fields, required properties of photoconductor arrays can be developed. Future far-infrared detector must meet these requirements to enable the study of magnetic fields in space.

Introduction

Magnetic fields may play central roles in the cycle of matter and energy in the interstellar medium (ISM), especially in star formation processes. To date, there has been no comprehensive survey of magnetic fields in the cold molecular ISM capable of revealing the context and details of the fields.

Magnetic fields may be traced using the Zeeman and Faraday effects at radio wavelengths and using linear polarization of background starlight (optical and near-infrared) and thermal dust emission (FIR and submm). However, only thermal dust emission polarization can probe deeply into the star forming clouds and trace magnetic fields in the cold ISM to kpc distances in the galaxy.

A large-scale survey of the inner regions of the Milky Way, of nearby examples of star forming clouds, and of the enigmatic infrared cirrus to reveal the properties of the magnetic field in the galaxy is a perfect match to NASA's Small Explorer (SMEX) program. Nevertheless, polarization observations place difficult requirements on instruments, on operations, and especially on detectors.

In addition the usual need for high quantum efficiency, low dark current, and high pixel count, polarization observations require unusually high signal-to-noise (in the range 150-1000:1), good photometric stability, and good immunity to charged particles.

Further, FIR polarimetry surveys conducted from SMEX or MIDEA platforms must contend with limited cryogen lifetimes, mass and volume limits, as well as cost and schedule constraints. My teams have developed SMEX proposals to conduct such surveys, including modeling detector characteristics in the space environment and folding these into realistic mission/survey scenarios.

The most recent of these efforts was called M4, for the *Milky Way Magnetic Field Mapping Mission*. M4 would feature a 20cm cold telescope, twin 32x32 Ge:Ga photoconductor arrays operating broadband near 95 μ m, a rotating half-wave plate and fixed wire grid for polarization analysis, and a short 3-4 month lifetime in its 500km altitude sun-sync orbit. Despite high marks for science, technical and mission implementations, the proposed SIRT/MIPS detector arrays have been flagged as not yet demonstrated to meet our S/N requirements. Such demonstrations should be performed as soon as possible.

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Magnetic Fields in Space

The central goal of M4 is to determine the magnetic field structure in the interstellar medium of the Milky Way Galaxy. Meeting this goal rests on answering four broad questions: (1) Are molecular clouds threaded by a common, Galactic magnetic field? (2) What role does the magnetic field play in the diffuse interstellar medium? (3) Are magnetic fields strong or weak relative to the energies and forces affecting molecular clouds? (4) How do magnetic fields thread star-forming regions? Answering these questions requires surveying vast areas of the galactic plane and molecular clouds for the signature of FIR linear polarization.

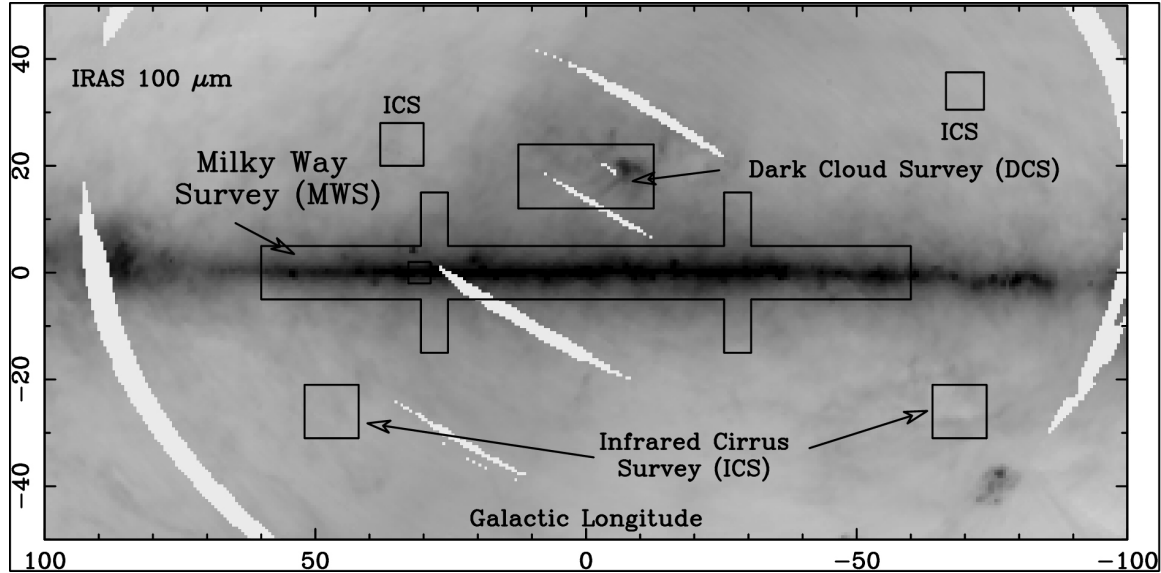


Figure 1: Partial IRAS sky map at 100 μ m wavelength projected in galactic coordinates showing the regions M4 will survey. These are a Milky Way Survey (MWS) of 1,400 sq. deg. toward the inner galaxy, a Dark Cloud Survey (DCS) of 300 sq. deg. toward the nearby Sco/Oph/Cen complex of dark clouds, and an Infrared Cirrus Survey (ICS) of 330 sq. deg. toward regions well-removed from the galactic plane.

The data needed to answer these questions must meet stringent requirements in order to allow extracting useful magnetic field directional information. These requirements include: (1) magnetic field orientations – the instrument/detector/data system must be able to measure magnetic field orientations to under 10 degrees position angle uncertainty; (2) area coverage – over 1,000 square degrees of the galactic disk, covering tens of degrees of galactic longitude and latitude, sampling hundreds of molecular clouds (see Figure 1) must be surveyed to be able to reveal the large-scale structure of the field and to test effects like the Parker Instability; (3) angular resolution – the pixel angular field of view must be comparable to the resolutions of ground-based millimeter wavelength molecular spectral line surveys (1-2 arcmin) to enable morphological matching of individual clouds, cores, and star forming sites; and (4) sensitivity and dynamic range – these must be adequate to enable accurate polarization measurements from 2-20,000 MJy/sr of surface brightness (see Table 1). Calculations for SOFIA, balloon altitudes, and space show that only from space can the faintest regions be probed with FIR polarization. Large-area surveys of modest brightness need space-based sensitivity.

Table 1: Comparison of Magnetic Field Target Surface Brightness with Instrument Sensitivity

Region of Study	100 μ m Surface Brightness [MJy/sr]	Within Sensitivity Range ? [for 1 hr, 150:1 S/N polarimetry]		
		SOFIA	Balloon-based	M4/SMEX
Galactic Center	400-20,000	[[[
Galactic Mid-Plane	40-400		[[
Dark Clouds	4-20		(ULDB only)	[
Infrared Cirrus	0.4-2			[

FIR Linear Polarimetry from Space – Constraints to Requirements

A rich history of FIR polarimetry observations from the KAO^{1,2} has revealed the polarization levels M4 needs to reach to conduct the indicated large-scale surveys for magnetic fields. From the measured KAO FIR polarization distribution (see Table 2), a requirement that M4 measure under 10 degrees position angle uncertainty, for an average polarization per position in the surveys of 2.5%, yields a S/N requirement of 150:1. For M4 to achieve under 7 degree uncertainty for 1% polarizations, it must reach a S/N of 600:1. These values are currently difficult to achieve with Ge:Ga photoconductors exhibiting transient effects.

Table 2: *Requisite Signal-to-Noise for Magnetic Field Mapping*

Polarization Distribution	P [%]	Signal-to-Noise Needed to Achieve Polarization Position Angle Uncertainties at or below:				
		10 deg	7 deg	5 deg	3 deg	1 deg
Upper 10%	6.7	50:1	70:1	100:1	200:1	450:1
Median	2.5	150:1	225:1	320:1	550:1	>1000:1
Upper 90%	1.0	400:1	600:1	800:1	>1000:1	>>1000:1

Ideally, FIR polarization measurements occur near the peak of the 16-18K cold dust blackbody, around 160-200 μ m. In SMEX and MIDEX observatories, however, cold telescope diameters are limited to about 20-30 cm (SMEX) and 30-50 cm (MIDEX) by the need for annular cryostats and rejection of Earth- and Sun-shine. In the case of M4, factors of sensitivity, pixel count, cryogen lifetime, and the need for good angular resolution favored operation near 100 μ m, somewhat off the cold dust emission peak.

Large area surveys designed to provide context for magnetic field investigations require large numbers of pixels in the resulting maps. Coupled with the short lifetimes of cryogenically cooled telescopes in near earth orbit, the large area maps require large numbers of detector pixels to complete the surveys before cryogen exhaustion. For the case of M4, the necessary surveys total about 2,000 square degrees at 2 arcmin pixel resolution, which demands FIR detector arrays with 32x32 pixels or more.

Detector Requirements Summary

The detector arrays needed for the conduct of large-scale mapping of magnetic fields from a space-based SMEX or MIDEX platform can be summarized as:

- Large array pixel counts (32x32 or higher) – needed to complete large-area surveys in limited time.
- FIR wavelengths (with central λ 's in the range 70-200 μ m) and with wide bandwidths ($\lambda/d\lambda < 3$) resulting in background-limited sensitivity (where the background is the zodiacal light)
- Low read noise (< 150 e/pixel/read) – to permit the short integrations needed for polarimetry
- High QE (> 10%)
- High dynamic range (> 100:1) – because the galactic plane is *not* a faint, uniform scene
- High achievable S/N (> 150:1 req'd; 1000:1 goal) – needed to obtain magnetic field position angle uncertainties under 10-7 degrees.
- Capable of good photometry to 1% - although differential *polarimetric* observations intrinsically boost this to 0.1% for polarization values under 10%
- Operation at SFHe temperatures (1.5-2K) – lower temperatures are too costly for a SMEX program
- Good immunity to charged particles and good gain stability and/or recalibration stability – a problematic issue for Ge:Ga photoconductors (see papers by Haegel and Young, this volume).

Baseline M4

The M4 observatory (Figure 2) consists of a cold (5.5K) telescope and instrument (2K) mounted on a small, high performance 3-axis stabilized spacecraft bus. M4 will fly in a 500km, sun-sync orbit with continuous illumination of its solar panels, avoiding eclipses during its 3-4 month flight. The forward sun shade and reflective coatings on the cryostat underside reject earth radiation. Inside the M4 instrument is a cold, 20cm diameter wide-field telescope, an annular dewar to hold the 63 liter of SfHe cryogen, an ejectable aperture cover, and an instrument/detector bay located behind the aluminum primary mirror.

Figure 2: Cutaway view of the M4 cryostat, telescope, and instrument volume. Spacecraft bus is not shown.

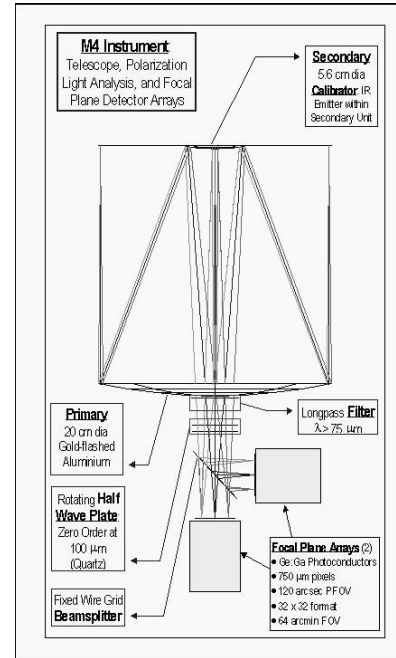
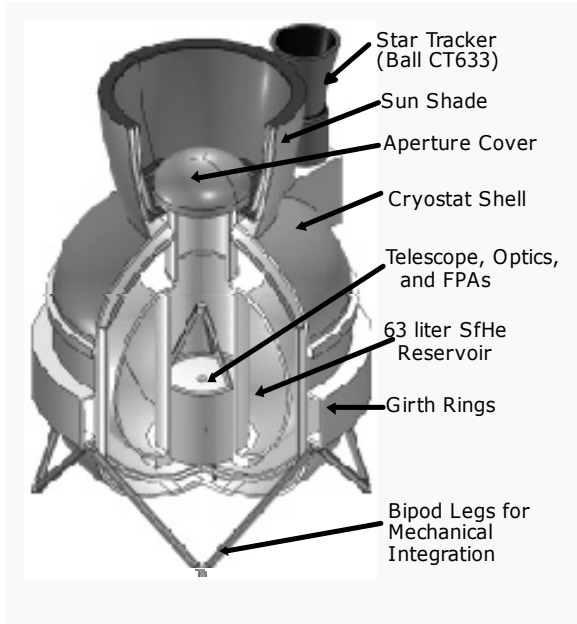


Figure 3: Ray-tracing of M4 telescope, light analysis optics, and detector array locations.

Polarization light analysis (Figure 3) consists of a rotating half-wave plate preceding a fixed, 45 degree wire grid which directs the two polarization senses onto two 32x32 Ge:Ga detector arrays. Bandpass action is provided by a long-pass filter and the long wavelength cutoff of the detectors. Detector calibration is performed using frequent (0.07 Hz) flashes from an IR stimulator (e.g., Beeman, this volume), located in the telescope secondary reflector. The baseline detectors for M4 are identical to the 32x32 pixel Ge:Ga unit in SIRTf's MIPS instrument. These will provide 2 arcmin angular resolution pixels across more than a 1x1 degree instrument field of view. Operating temperature will be between 1.8 and 2.2 K.

Summary and Recommendations

The large-scale distribution and properties of magnetic fields in the cold, star-forming interstellar medium of the Milky Way galaxy are largely unknown. A small mission, like M4, designed to specifically survey vast regions for magnetic field properties would reveal this otherwise invisible and important galactic constituent. FIR polarimetry, conducted using a small, cold telescope and background-limited instrument in near-earth orbit, could obtain the necessary data. Given the SMEX constraints of cost, mass, and volume bolometers are less favored than photoconductors as the detectors of choice.

However, we lack critical information regarding the operation of Ge:Ga unstressed array detectors for high signal-to-noise applications like polarimetry. These detectors should be characterized for such operation and perhaps optimized to remove/reduce the “hook” effect and other transient and illumination history effects.

References

- ¹ Platt, S. R., et al. 1991, PASP, 103, 1193.
- ² Hildebrand, R. H. et al. 1995, in Airborne Astronomy Symposium on the Galactic Ecosystem: From Gas to Stars to Dust, ed. M.R. Haas, J.A. Davidson & E.F. Erickson (San Francisco: ASP), p. 397.